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A.C.C. Villari and the SPIRAL group.

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The accelerated ISOL technique is presented as an introduction to the present status of the SPIRAL facility. SPIRAL is based on the very high intensity light and heavy ion beams available at GANIL. The facility will deliver radioactive beams with energies in the range between 1.7A and 25A MeV. The presently target-ion source production system, as well the new developments undertaken by the target ion-source group at GANIL are presented.

1. INTRODUCTION.

The understanding of the properties of the atomic nucleus far from the stability valley presupposes, first of all, the production of different species with enough intensity, allowing a careful study of their exotic properties. The pioneering efforts of ISOLDE [1] at CERN, followed by other equally important centres based on the so-called Isotopic Separation on-line (ISOL) technique, have contributed much to our present knowledge of the atomic nucleus far from stability. Nevertheless, important progress on the study of the fundamental properties of these nuclei came about when intense heavy-ion beams became available and the first results of experiments using fast radioactive ion beams (RIB) appeared. The world-wide known example is the first measurements of the interaction cross sections for light nuclei, made at the BEVALAC, USA by Tanihata and collaborators [2], which provided the first evidence for the existence of an unexpected halo for the nucleus ^{11}Li. From the first experiments in 1985, reactions using RIBs from projectile fragmentation has also been used at GANIL-France, GSI-Germany, MSU-USA, JINR-Dubna and RIKEN-Japan to produce and study reactions induced by radioactive beams. Separators have been built at these centres in order to maximise the RIB production and purity. All these facilities have in common the fact that RIBs are produced by projectile fragmentation at energies between 40A and 2000A MeV. It turns out from the principle of production and separation using a spectrograph, also called in-flight method that the optimum efficiency of the process is reached when the RIB has a velocity similar to that of the primary beam [3]. The production process, however, does imply losses in intensity and/or quality of the secondary beam, which become increasingly important as the beam is slowed down. From this point of view, the study of secondary beam reactions at low energies using intense RIBs needed a different production method. Only the coupling of the ISOL technique with a post-accelerator provides for production and separation of RIBs with subsequent acceleration, opening up the study of nuclear reactions with intense radioactive ion beams at low energies, in particular near the Coulomb barrier.

The first accelerated radioactive ion beam produced with ISOL technique has been obtained at CRC-UCL, Louvain-La-Neuve, Belgium [4,5]. The radioactive beam of ^{13}N has been obtained from the reaction ^{13}C(p,n)^{13}N impinging protons of 30MeV from the CYCLONE-30 Cyclotron on a powder ^{13}C target. The radioactive ^{13}N was transferred into an ECRIS (Electron Cyclotron Resonance Ion Source) through a long transfer tube. The atoms were ionised, extracted and injected in the cyclotron CYCLONE.

Following on the same principle, but using different ion sources and accelerators, HRIBF – ORNL have presently a large variety of accelerated available beams from Fluorine to fission products [6]. Using the same technique, but in a different approach, ISAC – TRIUMF is also producing RIBs for experiments near the Coulomb barrier at Vancouver, Canada [7]. In Europe, another three accelerated ISOL facilities are presently being built: REX-ISOLDE at Cern [8], EXCYT – LNS at Catania [9] and SPIRAL – GANIL at Caen [10].

The SPIRAL facility, based also on the ISOL method, will provide for production and separation of RIBs, with subsequent acceleration by the CIME cyclotron to energies between 1.7A and 25A MeV, the highest available energy of all existing accelerated ISOL RIB facilities. Another important difference between SPIRAL and the present ISOL facilities is the variety of available combinations beam – target, due to the fact that GANIL is a Heavy Ion facility. This particularity allows SPIRAL to use the most resilient and efficient couple beam-target in most cases and can be crucial in defining the production performances of the facility.

In the following sessions a short description of the ISOL method and a full description of the SPIRAL facility with its expected intensities are given.

2. ISOL PRINCIPLE.

In the ISOL on-line production the primary production beam impinges a thick target producing radioactive species via nuclear reactions. After the production in the target, the radioactive species diffuse in the crystalline structure of the target, release from its surface and are transferred through a conductor to an ion source. The atoms are subsequently ionised, extracted and selected by a separator. After selection, the produced beam can be directly used for low energy experiments or can be injected in an accelerator.

The overall efficiency of the production processes is a product of mainly 4 independent factors as follows:

$$\xi = \xi_{Diff} \cdot \xi_{Eff} \cdot \xi_{Ion} \cdot \xi_{Acc/Tran} \qquad (1)$$

Where each component stands for the diffusion, effusion, ionisation and acceleration/transport efficiencies. The diffusion efficiency refers to the probability of a certain radioactive atom to be released form the target material before its decay. The effusion efficiency denotes the probability of the radioactive atom to reach the ion source zone (i.e. the probability to be transferred from the target to the ionisation region) before decaying. This part, in our case, takes into account by definition the delay inside the ion source, do to collisions in the walls before its capturing by the source plasma. The ionisation efficiency is the probability of the atom to be ionised at a given charge state (1+ or higher, if necessary). This efficiency is independent of the lifetime of the radioactive element because, in our definition, the time-dependent part has been considered in the effusion efficiency and the ionisation time is negligible when compared with the lifetimes considered. Finally, the acceleration/transport efficiency is the probability of an ion to be accelerated and/or transported from the ion source to the detection point. This efficiency is also independent of the lifetime of the radioactive element because it is negligible when compared with the radioactive lifetimes.

Therefore, considering this definition, the equation (1) can be divided into two main parts. The first one, which is the product of the diffusion and the effusion efficiencies ($\xi_{Diff} \cdot \xi_{Eff}$) is time dependent, which means that it is a function of the lifetime of the radioactive atom considered. The second part, which is the product of the ionisation efficiency and the acceleration/transport efficiency ($\xi_{Ion} \cdot \xi_{Acc/Tran}$), is independent of the lifetime and can be, in principle, determined off-line using a stable probe of the element studied.

In the following example, experimental diffusion-effusion efficiencies of the SPIRAL carbon target, which consists in thin slices of carbon (0.5 mm) in a conical geometry [11] are plotted as a function of the target temperature (fig. 1) for ^{35}Ar (1.78s). Different grain microstructures of the carbon are compared, i.e. 1 μm, 4 μm and 15 μm of diameter. The results show an important enhancement of the diffusion - effusion efficiency for 1 μm microstructure when compared with the 4 μm and 15 μm. While 100% of efficiency is reached at 2000 K temperature for the 1 μm carbon, only 30 % and 10 % has been measured for the 4 μm and 15 μm, respectively. The continuous and dashed lines represent the theoretical calculations of the diffusion efficiency assuming the indicated Arrhenius coefficients. This simple example shows how sensitive is the overall efficiency of an ISOL system. The delays involved on the production process are critically dependent of the material and chemistry on the target-ion source system.

2. SPIRAL OVERVIEW.

The IN2P3/CNRS, DSM/CEA and the Regional Council of Lower Normandy funded the SPIRAL project at GANIL in December 1993. Under the project leader M. Marcel Lieuvin, a large collaboration [12] between laboratories in France and Europe has been established in order to construct and develop SPIRAL. The project is based on the ISOL technique for production of Radioactive Ion Beams (RIB) with post acceleration.

Today GANIL produces beams with intensities reaching $6x10^9$ to $2x10^{13}$ pps for ions from ^{238}U to ^{12}C at energies from 24A to 96A MeV (see THI project for details [13]). The primary light or heavy-ion beam accelerated by the GANIL cyclotrons bombards a production target located inside a well shielded area beneath ground level in the machine building. In addition to the target-ion source system, both high and low-energy "front-ends" are installed inside the cave. A view of the cave is shown in figure 2. Importantly, each component can be remotely removed from the cave. The radioactive atoms produced by nuclear reactions are released from the target kept at high temperature (~2300 K), and pass through a transfer tube into a full permanent magnet ECRIS. The radioactive atoms are ionised up to charge states corresponding to q/m = 0.09 to 0.40. After extraction from the ECRIS, the low-energy RIB (acceleration voltage from 7kV to 34kV) are selected by a relatively low resolution separator ($\Delta m/m = 4x10^{-3}$) and injected into the new K=265 (Bρ=2.344Tm) compact cyclotron CIME. The corresponding energy range varies from 1.7A to 25A MeV. After acceleration, the RIBs are selected in magnetic rigidity by the modified α-shaped spectrometer and directed to the existing experimental areas.

2.1. The production system.

For the commissioning of SPIRAL, a solution based on an external carbon target linked to the ECR NANOGAN-III source by a short and cold transfer tube has been chosen. This simple system will deliver the first noble gas radioactive ion beam for SPIRAL. The carbon target has been chosen due to its excellent release properties, low atomic number and high sublimation temperature. This target guarantees the production of noble gases with reasonable yields and can be used with high power primary beams [14]. This requirement has necessitated the development of a special target design, which can withstand such power loads while conserving fast release properties. From the production point of view, the temperature of the target should be as high as possible and its profile should be as uniform as possible, in order to minimise the delay time between production and release. The temperature profile is related to the properties of the Bragg peak, which is particularly pronounced in the case of heavy ions. Therefore, a special conical design, which distributes uniformly the power density over the target volume has been developed (figure 3a). The temperature profile was measured experimentally at Louvain-la-Neuve, Belgium using a 6kW proton beam of 30MeV. The range and shape of the Bragg peak of 30MeV protons is very similar to ^{20}Ne at 100A MeV. The obtained data agrees perfectly with the simulations [11].

Particularly to the $^{6,8}He$ production [15], a specific carbon target, which is divided into two parts due to the long range of He in C, was developed (figure 3b). The ^{13}C primary beam only heats the first part (production target), while the second one (diffusion target) stops the fragmentation products, and is heated by an electric current through the axis. Both processes, i.e. target and projectile fragmentation, are useful in this case.

The NANOGAN-III [16] (Figure 4) is a compact full permanent magnet ECRIS developed for the first phase of the SPIRAL project. The magnetic circuit consists in a sextupolar magnetic structure for radial confinement superposed by two axially and one radially magnetised permanent magnet rings. This ion source has been designed for operation with a 10GHz transmitter. Its power consumption is of 200W when tuned for the best performance. NANOGAN-III is an evolution of the preceding model NANOGAN-II, which worked at 14.5GHz. The new version, even working at lower frequency, has several advantages. In order to lower the magnetic field in the centre of the plasma chamber, one of the permanent magnet rings has been removed. This decreased the cost and the weight of the ECRIS to 4/5 of the preceding one. The transmission of the beam through the separator has been also improved, which means that the emittance of NANOGAN-III is smaller than the preceding version. The ion source is linked to a carbon target by a cold and short transfer tube. This allows efficient production of noble gas elements with reasonable suppression of condensable contaminants. The overall efficiency of the system for the production of ^{35}Ar (8+) is better than 10%.

The ionisation efficiency - all charge states - of Ar ions has been measured to be better than 95% when NANOGAN-III is tuned in order to maximise the 8+ charge state. The comparison between the off and on-line charge state distributions, attests that the ion source is almost insensitive to the heating and to the presence of the beam on the target.

The radioactive beams intensities, which will be soon available at SPIRAL are listed in table 1. This list will be extended gradually as soon as the new target-ion source developments will be available. More details are given in the session 3.

2.2. The cyclotron CIME.

CIME (Cyclotron pour Ions de Moyenne Energie) [17] is a room temperature compact cyclotron of K = 265 with an average magnetic field between 0.75 and 1.56T and an ejection radius of 1.5m (figure 5). The energy range is 1.7A to 25A MeV. The beam emittance at injection is limited to 80π mm mrad and at ejection it is below 10π mm mrad.

The magnet is somewhat original and has 4 return yokes made of stacked thick slabs. This structure was chosen not only for its compactness but also for the resulting field homogeneity and low fabrication costs. The design of the RF resonators is rather classical with a cantilever dee and a sliding short circuit using spring contacts around the stems. One difficulty has been the design of a structure sufficiently rigid to avoid unacceptable sag of the dee and temperature dependent deformations.

The injection into the cyclotron is made axially using a Mueller inflector of radius 34 mm. This inflector has been optimised for the 3rd harmonic, corresponding to an energy range of about 4.8 to 11A MeV. The harmonics 2,3 and 4 can be accelerated with this central geometry. For harmonic 5, corresponding to the energy range 1.7A to 2.5A, a new inflector with a radius of 45mm and a couple of new dee noses have been designed.

The beam extraction is performed using two electrostatic and two magnetostatic channels with variable positions.

The diagnosis of the beam inside the cyclotron involves particle detectors, like Silicon and plastic detectors, allowing for the tuning of beams with very low intensities.

The separation between isobars will be performed for the most part by the cyclotron (which is a good spectrometer for fast ions [18]) with a resolution of $\Delta m/m \sim 5 \times 10^{-4}$. It is also possible to improve the resolution of the cyclotron with an appropriate de-tuning of the isochronism during the acceleration of the ions. This procedure can improve the resolution in mass to $\Delta m/m \sim 1 \times 10^{-4}$ [19]. Additional separation can be achieved by placing a stripper foil or a degrader in the dispersive focal plane of the spectrometer. In the latter case, however, significant losses in RIB intensity can occur. In the cases where a mono-tour extraction is achieved, the isobars are extracted with a phase shift proportional to their masses. Using the Radio Frequency (RF) signal of the cyclotron for tagging each event or beam particles, one could separate in time the events coming from different isobars. A mass resolution of $\Delta m/m \sim 2 \times 10^{-5}$ [20] can be achieved with this technique.

The cyclotron has been extensively tested with stable beams over its full functioning diagram. The overall beam transmission is around 40% with exception of the diagram borders - corresponding to the lowest and highest revolution frequencies. In these limiting cases and at the moment, the transmission decreases to 15%. The first two radioactive beams planned to be accelerated for the commissioning of SPIRAL will be ^{18}Ne (4+) at 7A MeV and ^{8}He (1+) at 4A MeV.

3. NEW BEAM DEVELOPMENTS.

The NANOGAN-III target ion source system is particularly well suited for on-line production of noble gases. Nevertheless, good efficiency for the production of Oxygen and Nitrogen isotopes was achieved with the same system. Preliminary results show that the diffusion of CO, CO_2, CN and other similar molecules are excellent in carbon matrixes. All these molecules are gaseous and stable, facilitating the transport from the target to the ion source zone. Inside the ECRIS, the molecules are mainly dissociated due to the high electron temperatures involved in the ECR plasma. The first on-line tests show that an overall efficiency of about 10% can be obtained. Particularly, very intense beams of neutron deficient Oxygen and Nitrogen could be obtained using ^{16}O and ^{14}N primary beams [21].

At GANIL, the development of ECRIS for monocharged production is intrinsically related to the charge booster project, i.e. the re-injection of the beam into a second ion source for charge multiplication, before the injection into an accelerator [22]. This important condition fixes not only the required efficiency but also the characteristics of the beam provided by the 1+ ECRIS. Another important aspect of the problem is the functioning cost. It is evident that a monocharged ion source is cheaper than a multicharged one. If one consider that the life-time of the production system is limited, a smaller and cheaper ion source is needed very close to the irradiation point.

The MONO1000 ECRIS [23] has been designed in order to have a large magnetised chamber of approximately 1 litre of volume, allowing one to place a target and/or a heating wall system with external cooling. The magnetic structure is made with two permanent magnets rings (total weight of 22.2 kg), which allows to create a closed 2000 Gauss surface at the wall of the plasma chamber. The plasma electrode is located at 1800 Gauss magnetic field. It has to be pointed out that no specific radial structure is used - the magnetic field is on revolution symmetry - and that the magnetic field in the extraction area presents a cylindrical geometry. During the first commissioning tests, the 2.45 Ghz microwave was injected into the large diameter (90 mm) cylindrical plasma chamber through a coaxial transition ended by an antenna.

In the first tests of the ion source the ionisation efficiency of the source has been measured injecting a quantity of Ar gas through a calibrated leak and tuning the source with He as support gas. The measured ionisation efficiencies for ^{40}Ar at 1+ and 2+ states were respectively 90% and 9% inside a root mean squared emittance of 27 π mm mrad at V=14kV extraction voltage. The ^{32}S beam production has been also studied injecting a calibrated quantity of the gaseous molecule of SO_2 in the source. This test - made with a maximum injected power of 20W - revealed an overall efficiency of ionisation for the compounds of ^{32}S of around 95%. This efficiency is distributed on 43 % of ^{32}S (1+), 1.8 % of ^{32}S (2+), 35 % of ^{32}SO (1+) and 24 % of the mixture $^{32}S_2$ (1+) with $^{32}SO_2$ (1+). It is clear that several different molecules are still present on the spectrum of the extracted ions. The ratio between the yield of this molecules and the ^{32}S (1+) beam varies strongly with the microwave power. Presently the tests were limited to around 20W due to the microwave coupling. A new coupling is being developed which could allow one to deliver one order of magnitude more power in the ion source.

The MONOLITHE (figure 6) [24] target - ion source ensemble is dedicated to produce monocharged ions of Li and Na. The target is split into two parts. The first one – cooled – is devoted to the production of the radioactive elements. The second one – heated to over 2300 K – is devoted to the diffusion and releasing of the radioactive ions, which are produced by projectile fragmentation. The very compact diffusion target is optimal for very short living isotopes, like ^{11}Li. The first on-line test of MONOLITHE showed an overall efficiency of the system of around 30% for ^{21}Na ($T_{1/2}$ = 22.5s). This value corresponds to the expected ionisation efficiency of the hot cavity. Tests will continue in order to improve the present performances.

4. SUMMARY.

In summary, the main principles of the accelerated ISOL method was described and the SPIRAL facility, which makes use of this technique, was presented.

The SPIRAL project is completed. The on-line production system has been successfully tested at the SIRa test bench and the accelerator CIME was tested with stable beams. Noble gas beams with intensities reaching several 10^8 particles per second will be soon available for experiments.

Presently, the functioning authorisation process is under way.

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The European laboratories which collaborate in SPIRAL are:
CRC-IPN, Louvain-La-Neuve, Belgium and ISOLDE/CERN-Genève

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Figure Captions:

(1) Diffusion and Effusion efficiency for ^{35}Ar (T1/2=1.78s) on a carbon graphite SPIRAL target as a function of temperature. The experimental points correspond to different microstructures (grain size) of the graphite. The continuous lines correspond to theoretical calculations using the above Arrhenius coefficients.
(2) View of the SPIRAL production cave.
(3) SPIRAL conical target (a) and the special design for He production (b). Both targets were built to work at 2kW maximum primary beam power.
(4) The NANOGAN-III target-ECRIS production system.
(5) The cyclotron CIME.
(6) The MONOLITHE hot cavity double-target - ion source, devoted to the production of Na and Li monocharged ions.

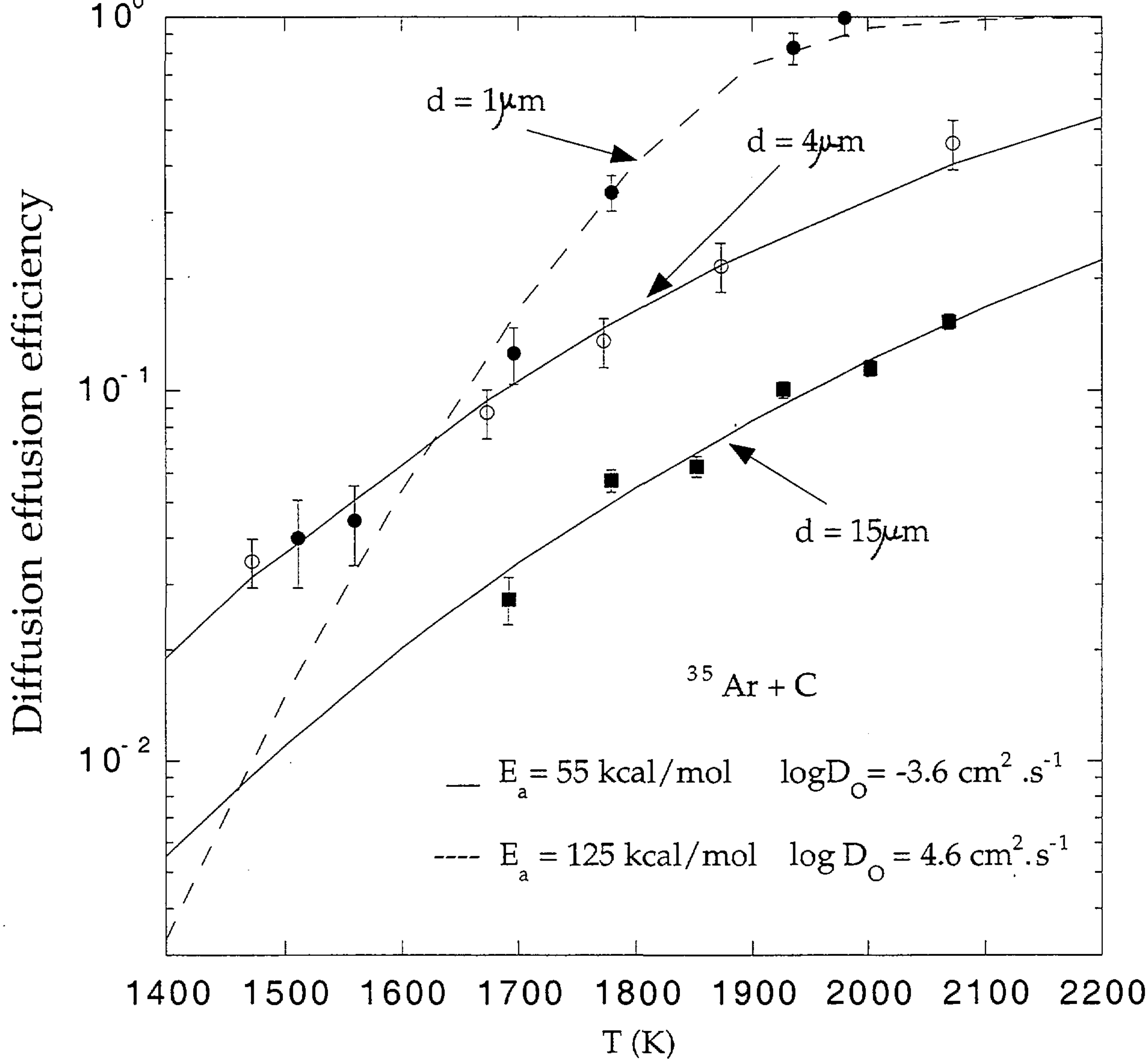
Table caption:

(1) Intensities for the first SPIRAL beams before acceleration. The yields for ^{6,8}He, $^{17-19}$Ne and $^{31-35}$Ar have been extrapolated from SIRa experimental results at 400W of primary beam power. The $^{72-77}$Kr yields have been measured on-line. The yields for the other isotopes have been calculated using the overall efficiencies measured on-line at SIRa. VLE: Very Low Energy. Only the yield of the charge state 3+ has been measured for the ^{31}Ar isotope. Higher charge states cannot be extrapolated.

Table 1.

Beam	Charge state	Intensity **BEFORE** acceleration (pps)	Energy min (A MeV)	Energy max (A MeV)	Primary Beam	Primary beam power (kW)	Energy of the primary beam (A MeV)
^{6}He(0.8s)	1+ 2+	1.0×10^{9} 8.0×10^{7}	2.7 6.8	7.2 22.8	^{13}C	2	75
^{8}He(0.12s)	1+ 2+	3.0×10^{6} 3.6×10^{5}	2.7 3.8	4.0 16.3	^{13}C	2	75
^{17}Ne (0.11s)	+(3-6)	1.5×10^{5}	2.7	24.3	^{20}Ne	2	95
^{18}Ne (1.7s)	+(3-6)	1.5×10^{7}	2.7	22.9	^{20}Ne	2	95
^{19}Ne (17s)	+(3-6)	2.5×10^{8}	2.7	21.6	^{20}Ne	2	95
^{23}Ne (37s)	+(3-6)	6.0×10^{7}	2.7	17.7	^{36}S	2	77
^{24}Ne (3.4m)	+(3-6)	2.0×10^{7}	2.7	16.4	^{36}S	2	77
^{25}Ne (0.61s)	+(3-6)	5.0×10^{5}	2.7	15.1	^{36}S	2	77
^{31}Ar (15ms)	+3	7	VLE (*)		^{36}Ar	2	95
^{32}Ar (98ms)	+(6-8) +9 +10	2.3×10^{3} 1.1×10^{3} 5.0×10^{2}	2.7 4.8 6.0	16.4 19.2 21.4	^{36}Ar	2	95
^{33}Ar (0.17s)	+(6-8) +9 +10	1.7×10^{5} 8.0×10^{4} 4.0×10^{4}	2.7 4.6 5.6	15.4 18.6 20.7	^{36}Ar	2	95
^{34}Ar (0.84s)	+(6-8) +9 +10	1.2×10^{7} 6.0×10^{6} 3.0×10^{6}	2.7 4.3 5.3	14.5 18.0 20.1	^{36}Ar	2	95
^{35}Ar (1.78s)	+(6-8) +9 +10	3.0×10^{8} 1.5×10^{8} 7.5×10^{7}	2.7 4.0 5.0	13.7 17.3 19.5	^{36}Ar	2	95
^{72}Kr (17s)	+(15-16)	8.0×10^{1}	2.7	12.9	^{78}Kr	0.2	73
^{73}Kr (27s)	+(15-16)	2.0×10^{3}	2.7	12.6	^{78}Kr	0.2	73
^{74}Kr (11m)	+(15-16)	1.0×10^{5}	2.7	12.3	^{78}Kr	0.2	73
^{75}Kr (4m)	+(15-16)	7.0×10^{5}	2.7	11.9	^{78}Kr	0.2	73
^{76}Kr (14.8h)	+(15-16)	3.0×10^{6}	2.7	11.6	^{78}Kr	0.2	73
^{77}Kr (74m)	+(15-16)	2.0×10^{7}	2.7	11.3	^{78}Kr	0.2	73

Figure 1.



Diffusion effusion efficiency
10^0
10^-1
10^-2
d = 1μm
d = 4μm
d = 15μm
35 Ar + C
E_a = 55 kcal/mol logD_O = -3.6 cm^2.s^-1
E_a = 125 kcal/mol log D_O = 4.6 cm^2.s^-1
1400 1500 1600 1700 1800 1900 2000 2100 2200
T (K)

Figure 2.

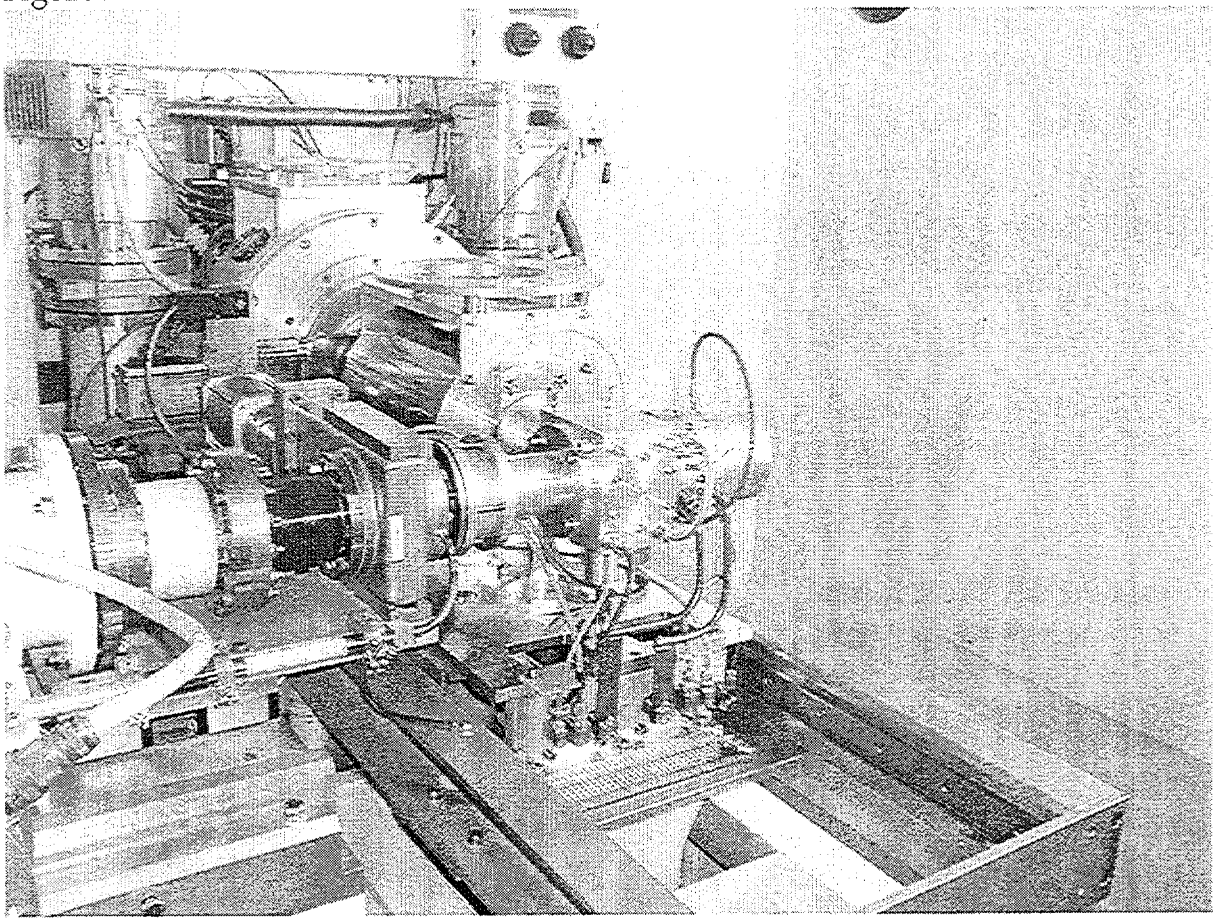


Figure 3.

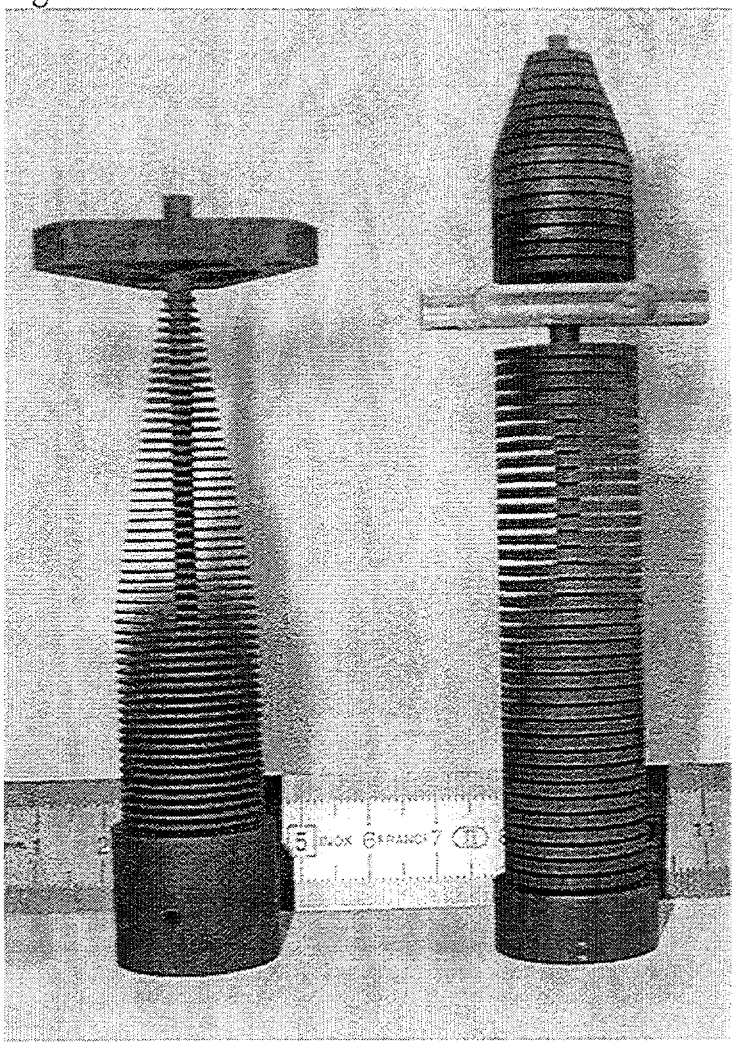


Figure 4.

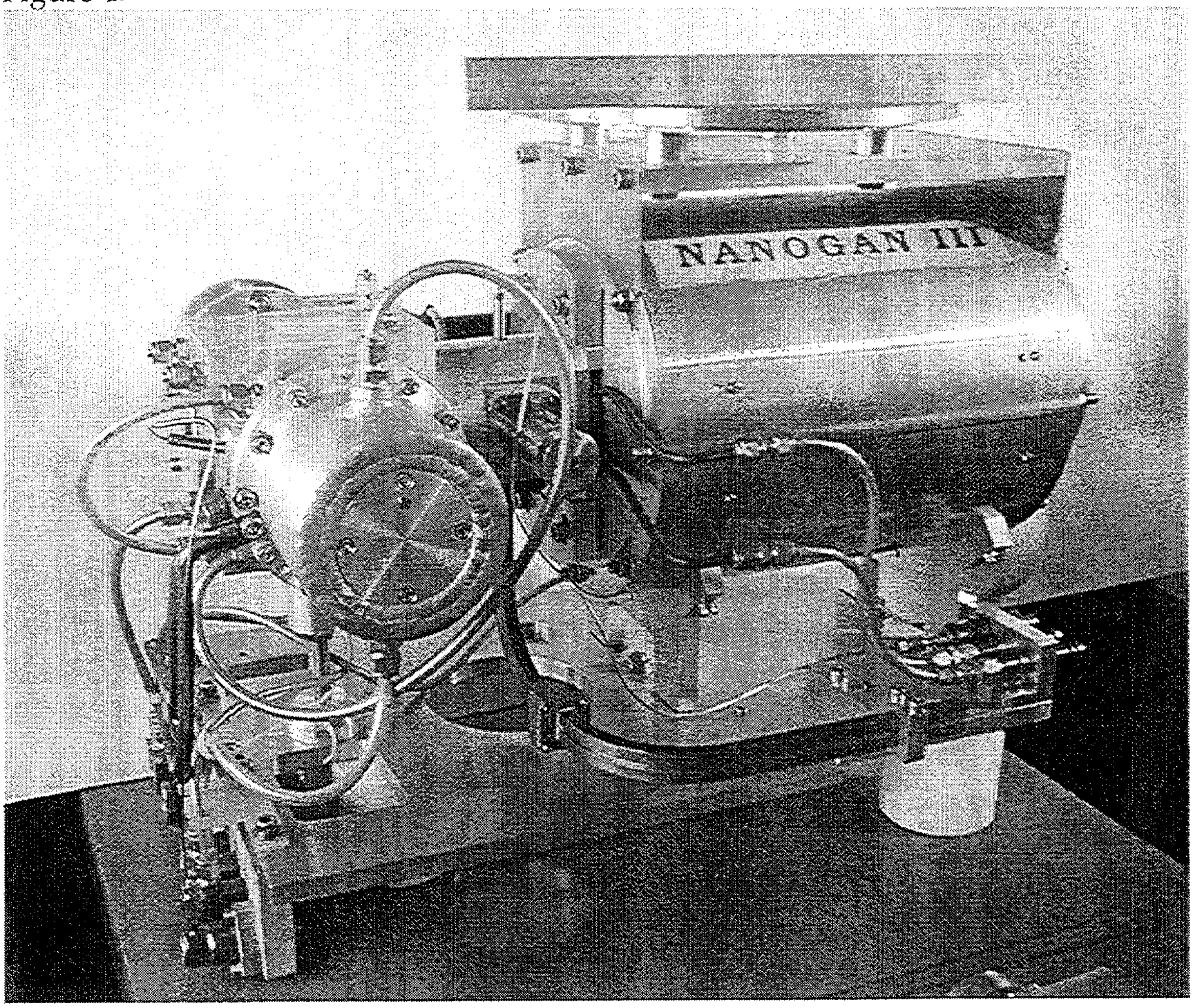


Figure 5.

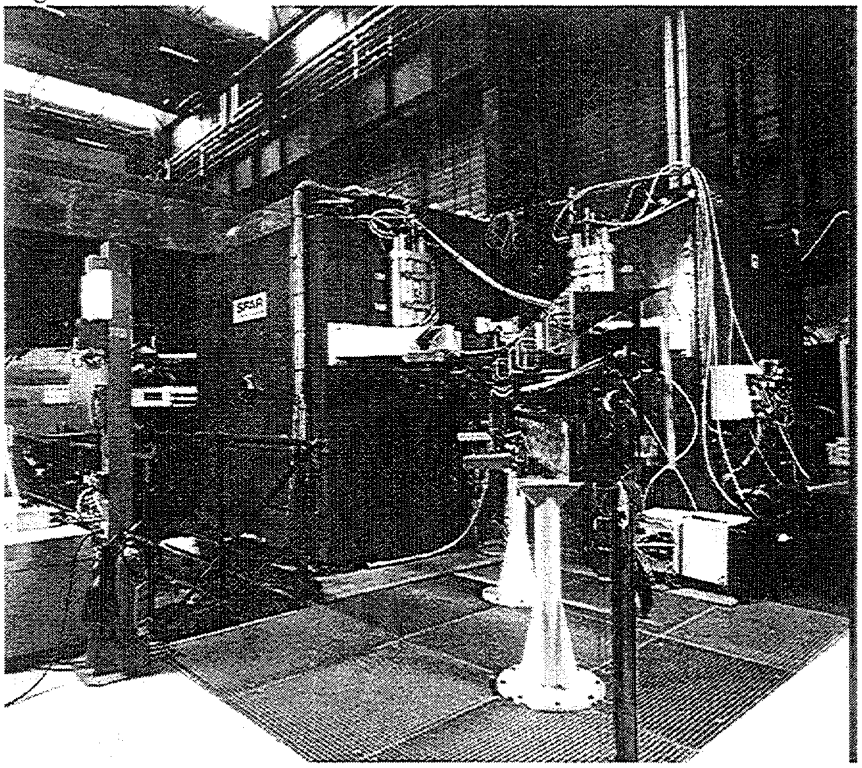
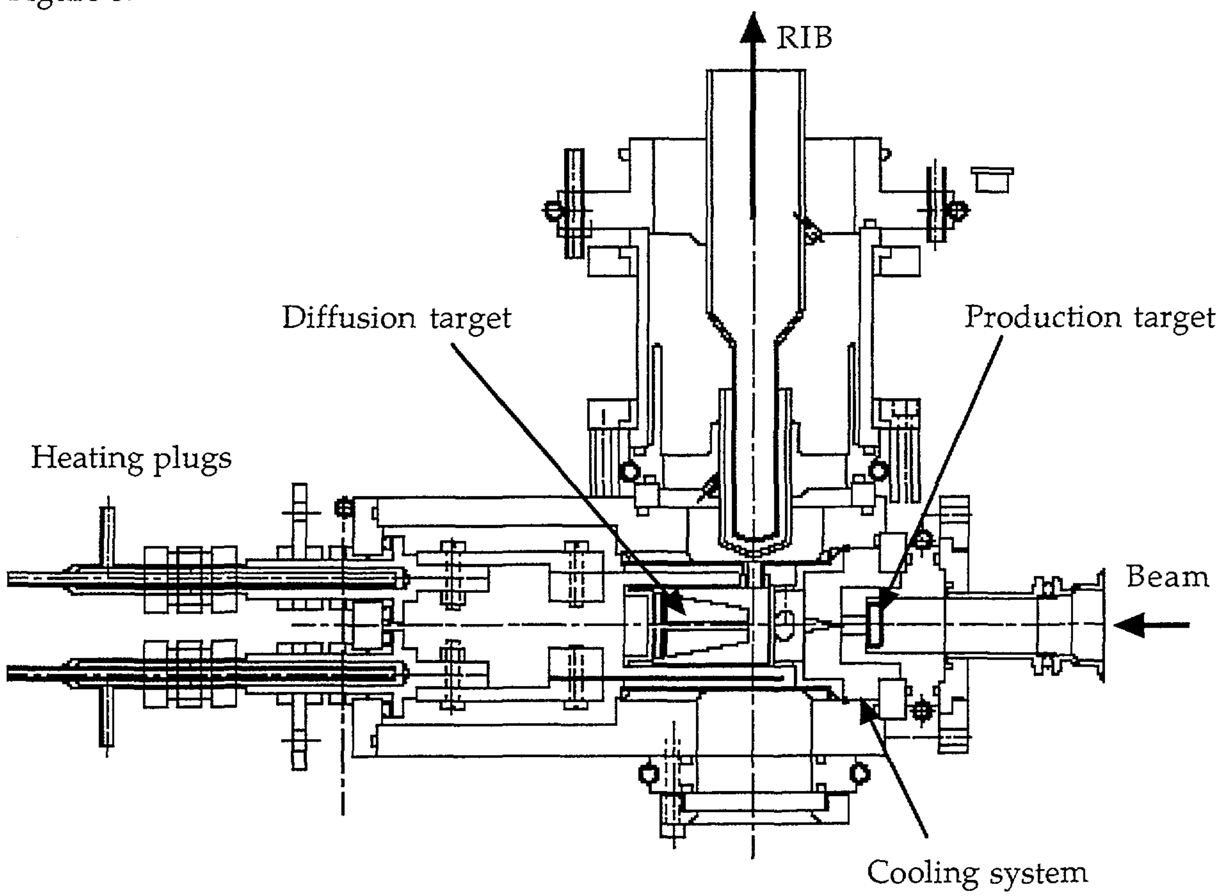


Figure 6.


RIB
Diffusion target
Production target
Heating plugs
Beam
Cooling system